Nuclear Structure Research Overview

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Lawrence Berkeley National Laboratory

U.S. DEPARTMENT OF ENERGY | Office of Science

BERKELEY LAB

Outline

- Who we are
- Our goals
- Recent highlights
- Near-term plans (<2018)
- Long-term plans (>2018)

The Nuclear Structure Group

People

Chris Campbell
Rod Clark
Heather Crawford
Mario Cromaz
Paul Fallon
Michael Jones (PD)
Augusto Macchiavelli
Marco Salathe (PD)

Main Activites

Structure Experiments and Research

GRETINA/ GRETA

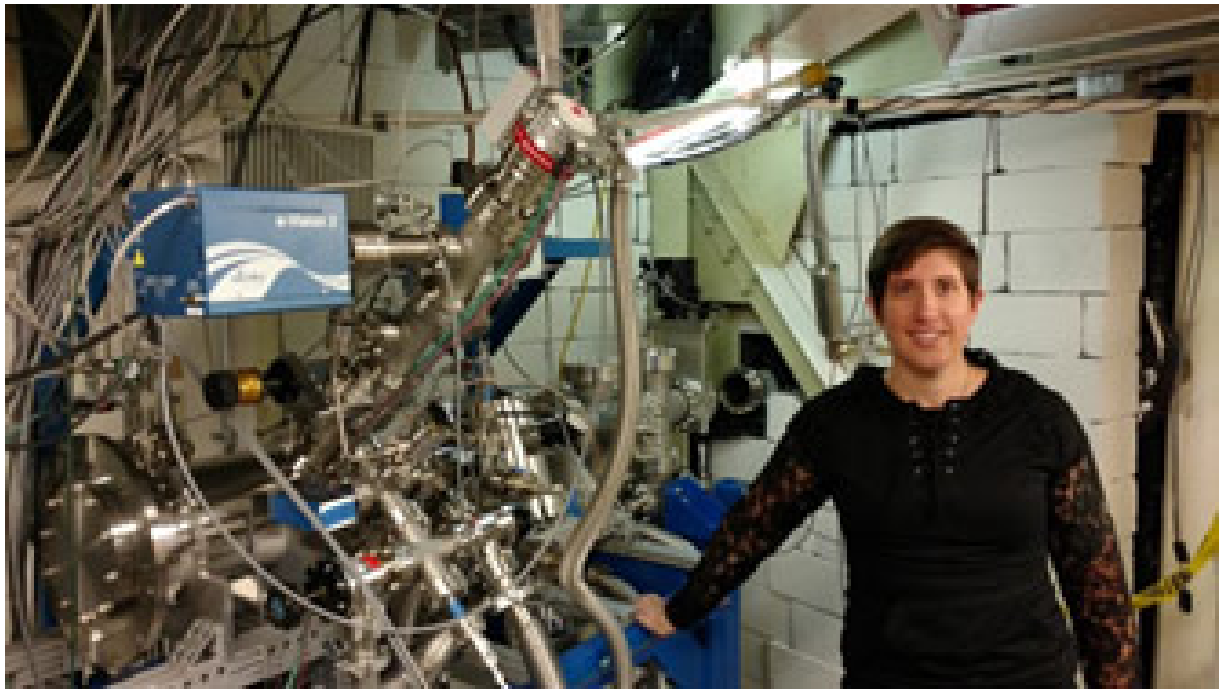
- We are the lead institution for GRETINA/GRETA - a core component of our effort. (At least 50% of manpower has been, and will be, devoted to GRETINA/GRETA).
- Heather will talk about GRETINA. Paul will talk about GRETA.
- We pursue research locally at the 88-Inch Cyclotron and at outside facilities.

Prizes and honors (since 2013)

2016 APS Tom W. Bonner Prize**: I-Yang Lee**
"For seminal contributions to the field of nuclear structure through the development of advanced gamma-ray detectors as realized in the Gammasphere device, and for pioneering work on gamma-ray energy tracking detectors demonstrated by the Gamma-ray Energy Tracking Array (GRETINA)"

APS Fellows:
2013 **Paul Fallon** "For use of gamma-ray spectroscopic techniques to elucidate the behavior of atomic nuclei..."
2015 **Rod Clark** "For contributions to our understanding of superdeformation...shears mechanism...heavy elements."
2015 **Lee Bernstein** "For work developing novel methods of determining neutron nucleus cross sections via high-resolution gamma-ray spectroscopy..."

And another one...



NSDs **Jackie Gates** has been awarded a 2017 **DOE Early Career Award**. The award will allow her to initiate a new program of experiments aimed at determining the masses and atomic numbers of super heavy elements, and then to delve further into understanding the nuclear properties of these nuclei by obtaining detailed information on their nuclear structure. More specifically, it will be used to commission the new heavy element mass separator, FIONA and to perform the first detailed studies of superheavy element masses and spectroscopy.

Some Facts and Figures

- 59 publications during 2013 – now
  (including 2 Invited Reviews, and 11 Letters)

- >50 talks, seminars, and oral presentations

- Actively engaged and serving the nuclear physics community:

NSAC Long Range Plan Writing Committee (Augusto Macchiavelli)
FRIB Science Advisory Committee (SAC)
FRIB Experimental Systems Advisory Committee (ESAC)
FRIB Users Executive Committee (Chair, Heather Crawford)
TRIUMF Experiment Evaluation Committee and Science Advisory Panel (EEC-SAP) (Chair, Rod Clark)
NSERC Subatomic Physics Advisory Panel
MSU/NSCL Program Advisory Committee
DOE OPA Review Committee for FRIB (Chair, Paul Fallon)
GRETINA Advisory Committee (GAC)
GANIL Program Advisory Committee
iTHEMBA Labs Program Advisory Committee
RIKEN/RIBF Users Group
Organizing Committee for Low Energy Community Meeting
Board of Directors for the Exotic Beam Summer School
APS-DNP Program Committee
DOE-SBIR Review Committee
ASCR-NP Exascale Requirements Working Group
GRETINA Users Executive Committee (Chair, Paul Fallon)
GRETINA Software Working Group (Chair, Mario Cromaz)
GRETINA Physics Working Group
+ Chair/Organizing Committees for many conferences and workshops

Synergies

- Work closely with other areas of the **Division**: Nuclear Data (Lee Bernstein), Heavy Elements (Jackie Gates), Applied Nuclear Physics (Kai Vetter), and 88-Inch Cyclotron Operations (Larry Phair)

- Strong ties with other areas of **Lab and Campus**: Engineering and Accelerator Technology and Applied Physics (ATAP) Divisions (GRETA and FRIB), and connections with Nuclear Engineering, Chemistry, and Physics Departments.

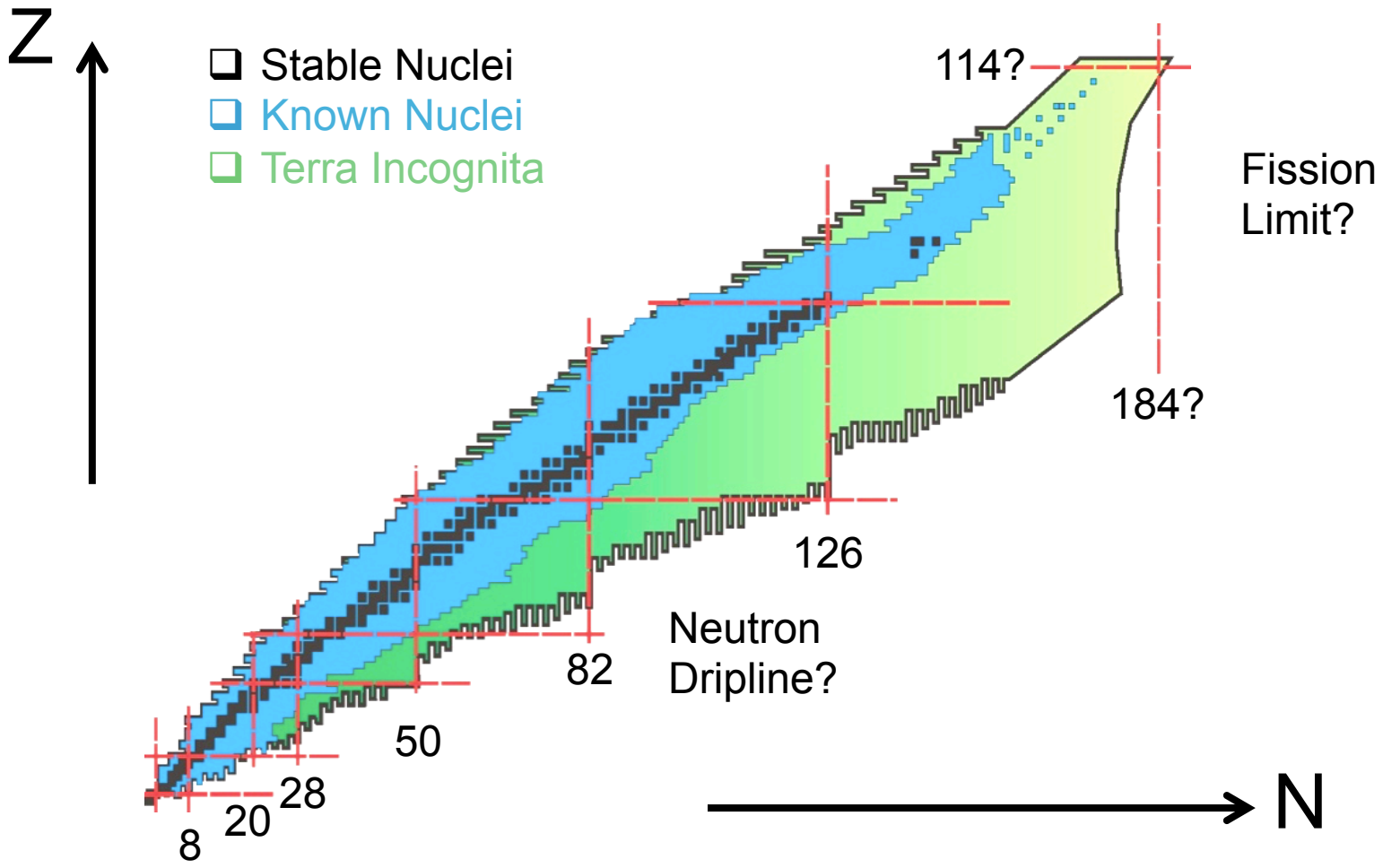
- Collaborations at major **National and International Facilities**: ANL, NSCL, RIKEN, TRIUMF

- Aligned with **National Priorities** as detailed in Long Range Plan. GRETA to play central role at FRIB.

Scientific Goal

"[To understand] the underlying nature of atomic nuclei and the limits to their existence"

-Reaching for the Horizon: The 2015 Long Range Plan for Nuclear Science



Strategy

1) Scientific leadership at FRIB

- GRETINA/GRETA

- Program at outside facilities (ATLAS, NSCL, RIKEN, TRIUMF)

2) World-leading research at the 88-Inch Cyclotron

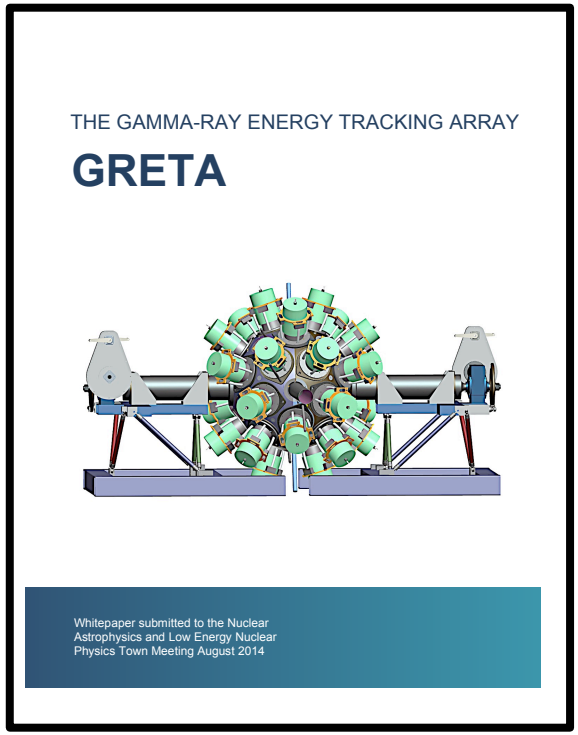
- Heavy-element spectroscopy

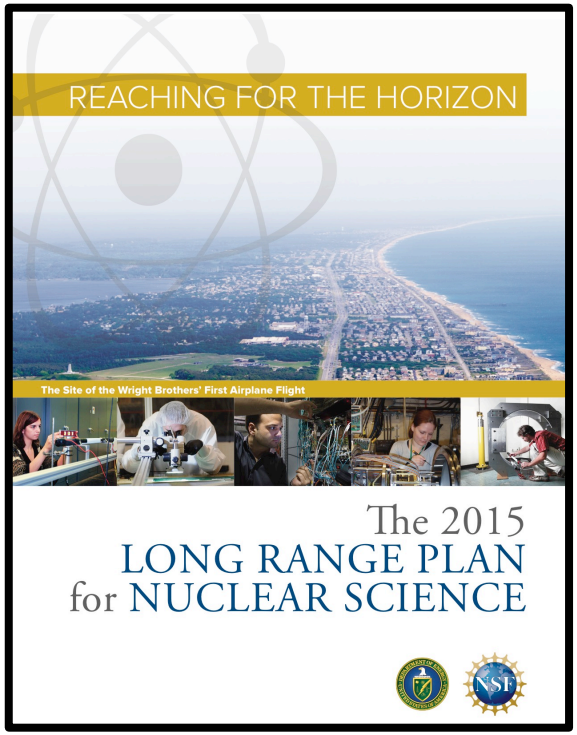
Aligned to priorities and recommendations in the 2015 NSAC Long-Range Plan

Recent Highlight: GRETA CD0

"GRETA will play a central role by adding significant capabilities to existing facilities, such as ATLAS, NSCL, and ARUNA facilities, and as a centerpiece at FRIB for the physics opportunities with both fast-fragmentation and reaccelerated beams."

-Reaching for the Horizon: The 2015 Long Range Plan for Nuclear Science, Pg. 95





CD0 awarded in September 2015. DOE OPA (CD1) review scheduled for April 2017.

Recent Highlight: Structure at the Neutron Dripline

"The territory of neutron-rich nuclei is the most fertile ground for research in nuclear structure"

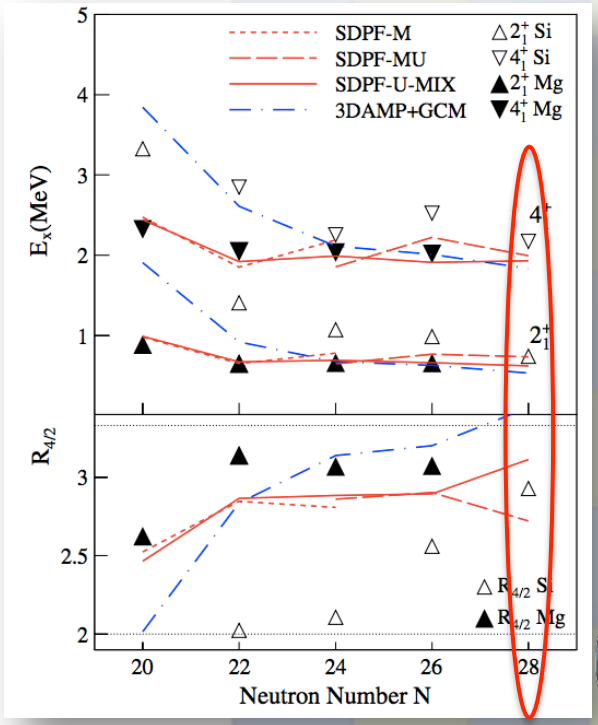
-Reaching for the Horizon: The 2015 Long Range Plan for Nuclear Science, Pg. 95

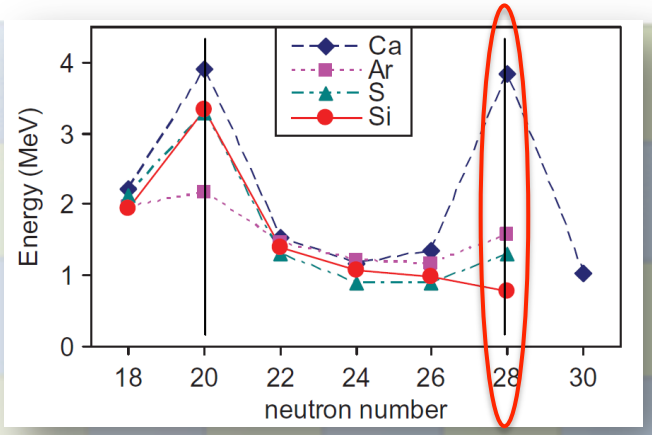
1) Neutron-rich Magnesium

2) Neutron-rich Carbon

Neutron Rich Magnesium Nuclei (1/2)

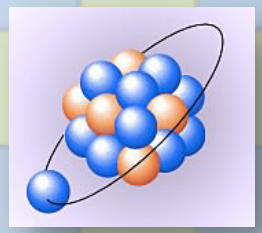
The neutron-rich Mg isotopes from *N*=20 to *N*=28 are deformed, bridging two eroded shell gaps.

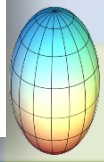


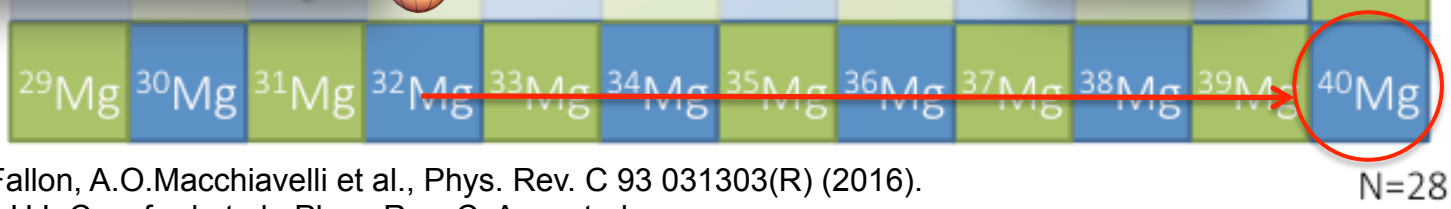


^{40}Mg is a (near)drip-line nucleus, at the intersection of *N*=28, where shapes are believed to be rapidly changing.

Low-l orbitals near the Fermi surface bring the possibility of nuclear halos.

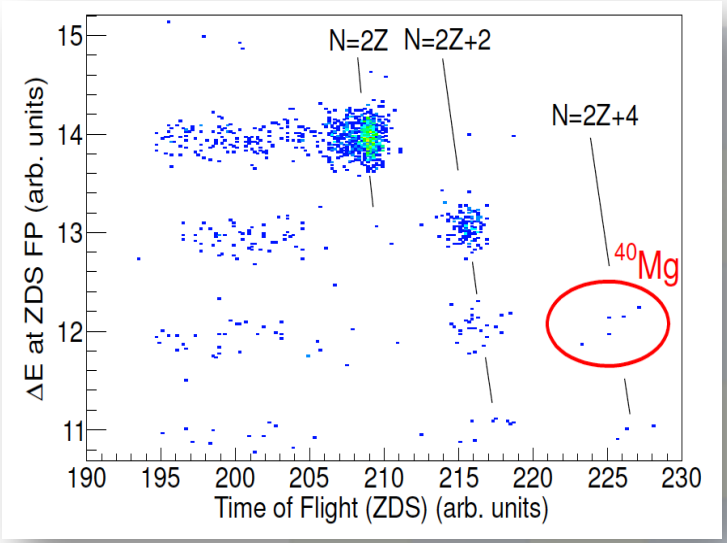




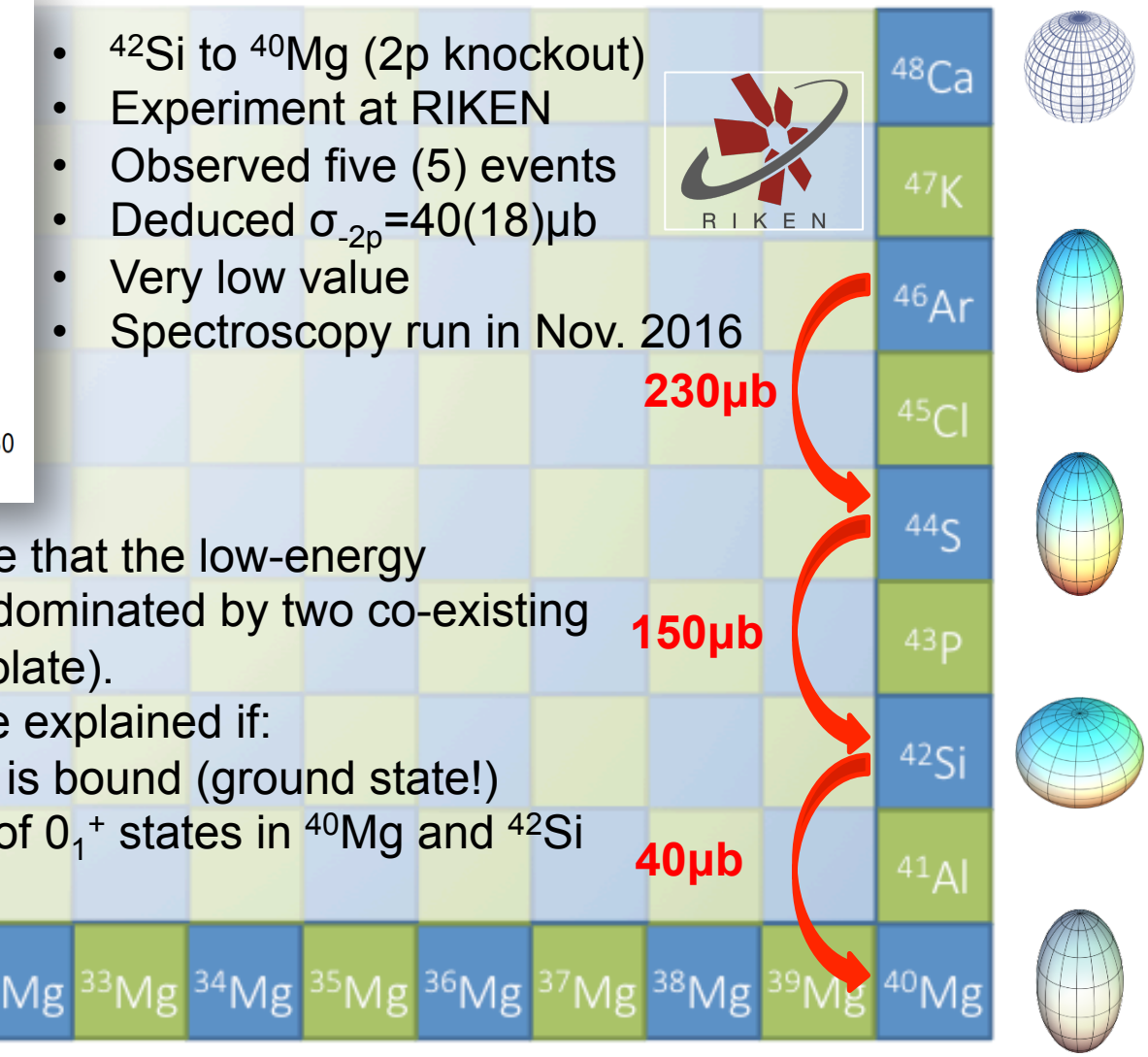


H.L.Crawford, P.Fallon, A.O.Macchiavelli et al., Phys. Rev. C 93 031303(R) (2016).
A.O.Macchiavelli, H.L.Crawford et al., Phys. Rev. C, Accepted

Neutron Rich Magnesium Nuclei (2/2)



- ^{42}Si to ^{40}Mg (2p knockout)
- Experiment at RIKEN
- Observed five (5) events
- Deduced σ_{-2p}=40(18)μb
- Very low value
- Spectroscopy run in Nov. 2016

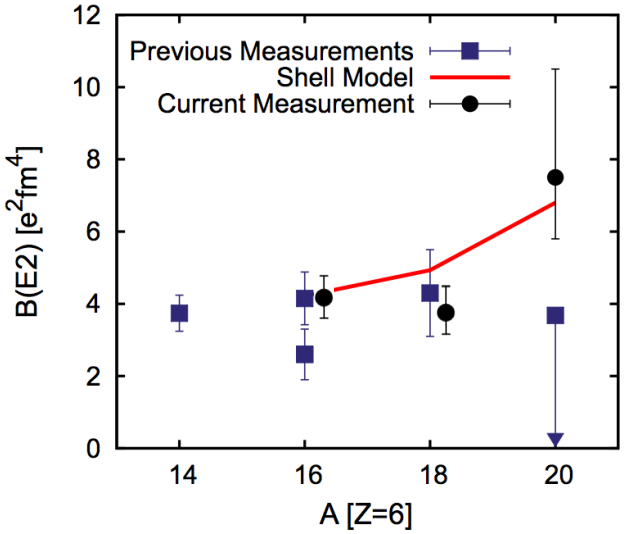


- Calculations and data indicate that the low-energy structure in ^{42}Si, and ^{40}Mg is dominated by two co-existing configurations (oblate and prolate).
- Low inclusive σ_{-2p} can only be explained if:
  i) ^{40}Mg has only one 0^+ that is bound (ground state!)
  ii) Dominant configurations of 0_1^+ states in ^{40}Mg and ^{42}Si are different

H.L.Crawford, P.Fallon et al., Phys. Rev. C 89 041303(R) (2014).

Neutron-Rich C Nuclei (1/2)

Year	Institution	Result	Interpretation
2004	RIKEN	Very low B(E2) in ^{16}C	Very low effective charge / decoupling of protons and neutrons
2008	LBNL	Lifetime measured and B(E2) deduced in ^{16}C	Value fits with shell model and systematics.
2009	RIKEN	Very low B(E2) derived in ^{20}C	Very low effective charge / decoupling of protons and neutrons
2011	LBNL/NSCL	Measured lifetimes in ^{16}C-^{20}C.	Values agreement with shell model and systematics.

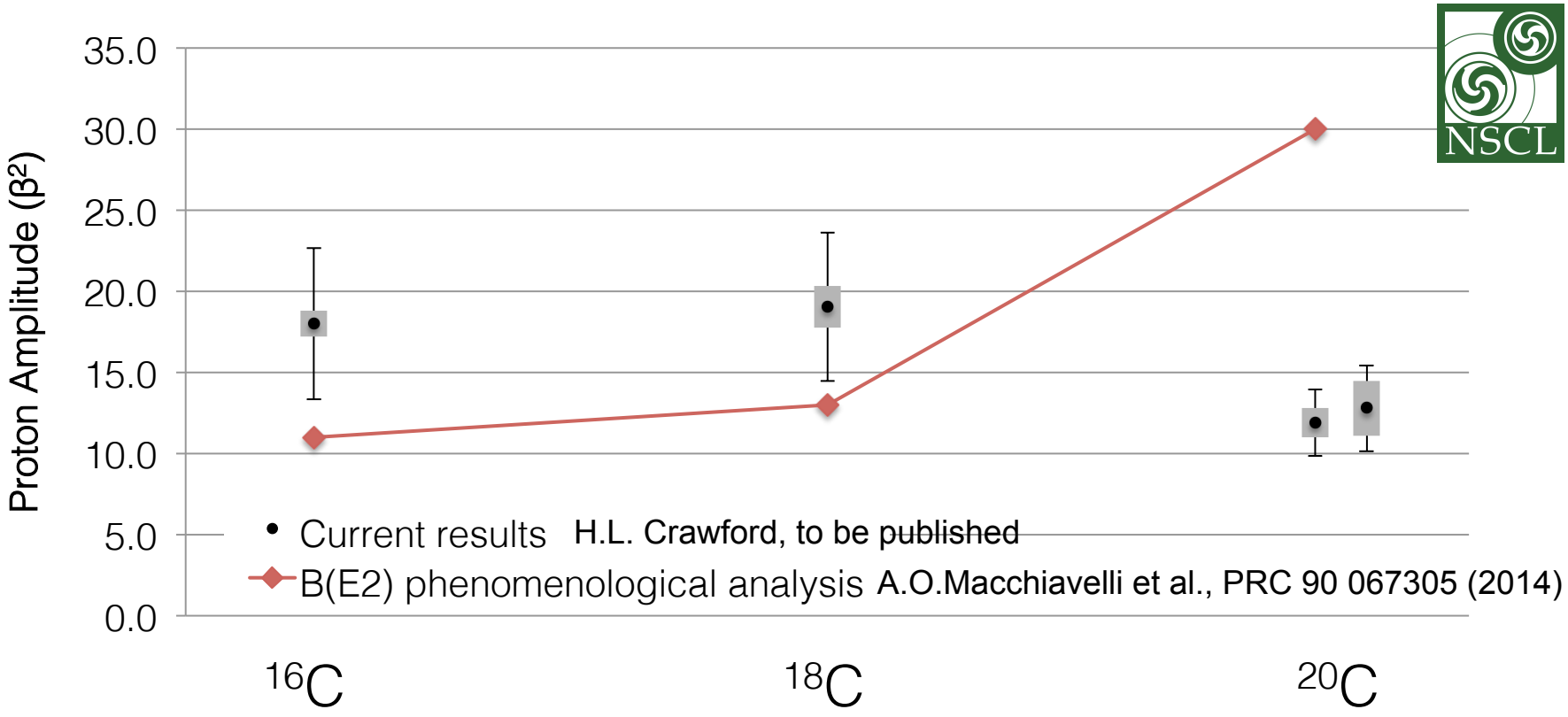


$$B(E2)=1/(2J_i+1)|M_n e_n+M_p e_p|^2$$

	M_p	M_n
^{16}C	1.28	9.39
^{18}C	1.76	11.16
^{20}C	**3.06**	11.48

Neutron-Rich C Nuclei (2/2)

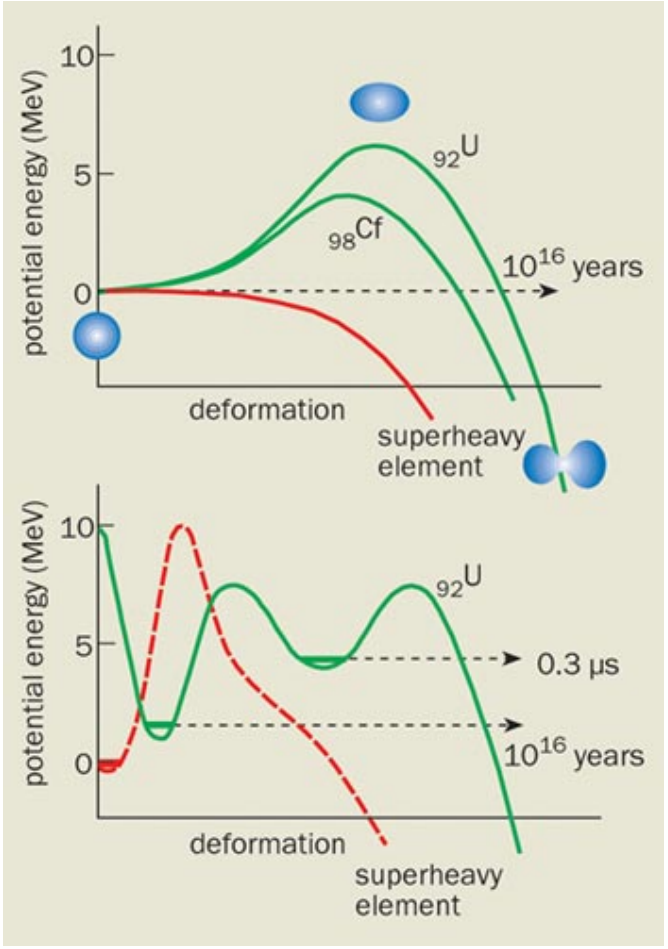
- Experiment at NSCL to quantify proton contribution to 2^+ excitation in $^{16,18,20}C$
- Primary Beam ^{48}Ca; secondary beams $^{17,19,21}N$; proton knockout into C isotopes
- CAESAR: High efficiency CsI(Na) detector covering large (~4π) solid angle to tag on 2^+ de-excitation gamma ray



Proton amplitude is essentially flat from N=10 to N=14, contrary to expectation

Structure of the Heaviest Elements

"Superheavy Nuclei and Atoms: A Tug of War of Forces"
-Reaching for the Horizon: The 2015 Long Range Plan for Nuclear Science, Pg. 47



1) What are the "magic numbers" for the spherical super-heavy nuclei?

➔ Locating the center of the "island of stability"

2) What are the magnitudes of the shell effects?

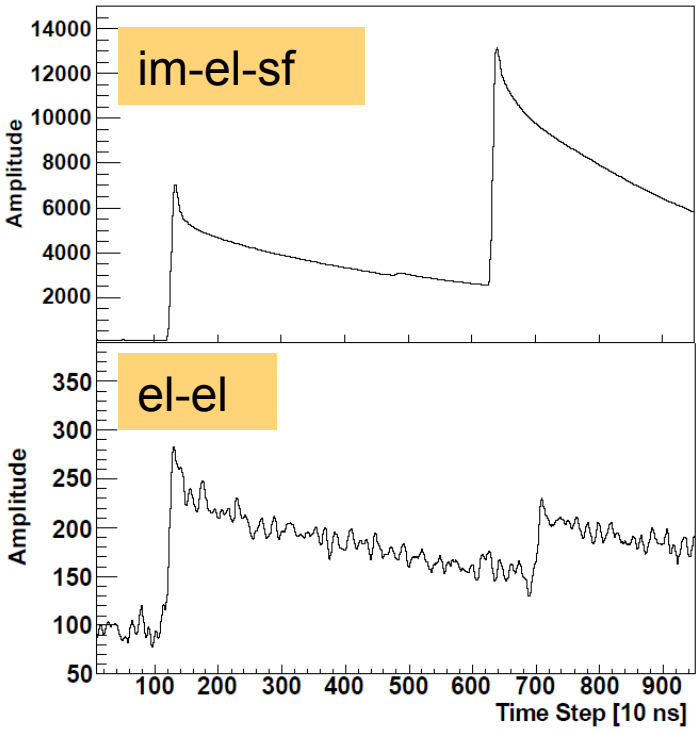
➔Extent and relative stability of island

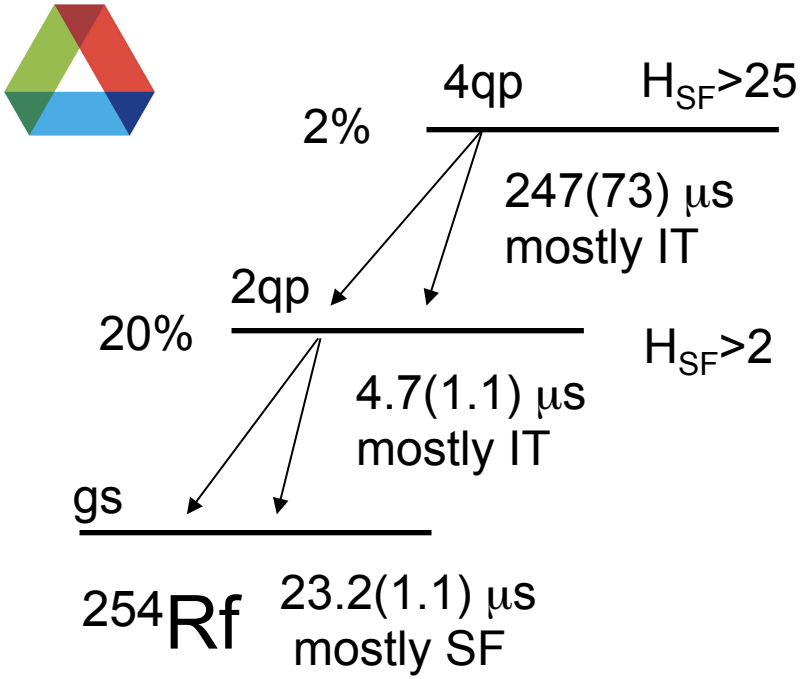
Key Experimental Information:

- single-particle structure
- stability against alpha decay
- stability against fission

J.Rissanen, R.M.Clark et al., Phys. Rev. C 88 044313 (2013) and Phys. Rev. C 90 044324 (2014)

Rutherfordium (Z=104) Spectroscopy





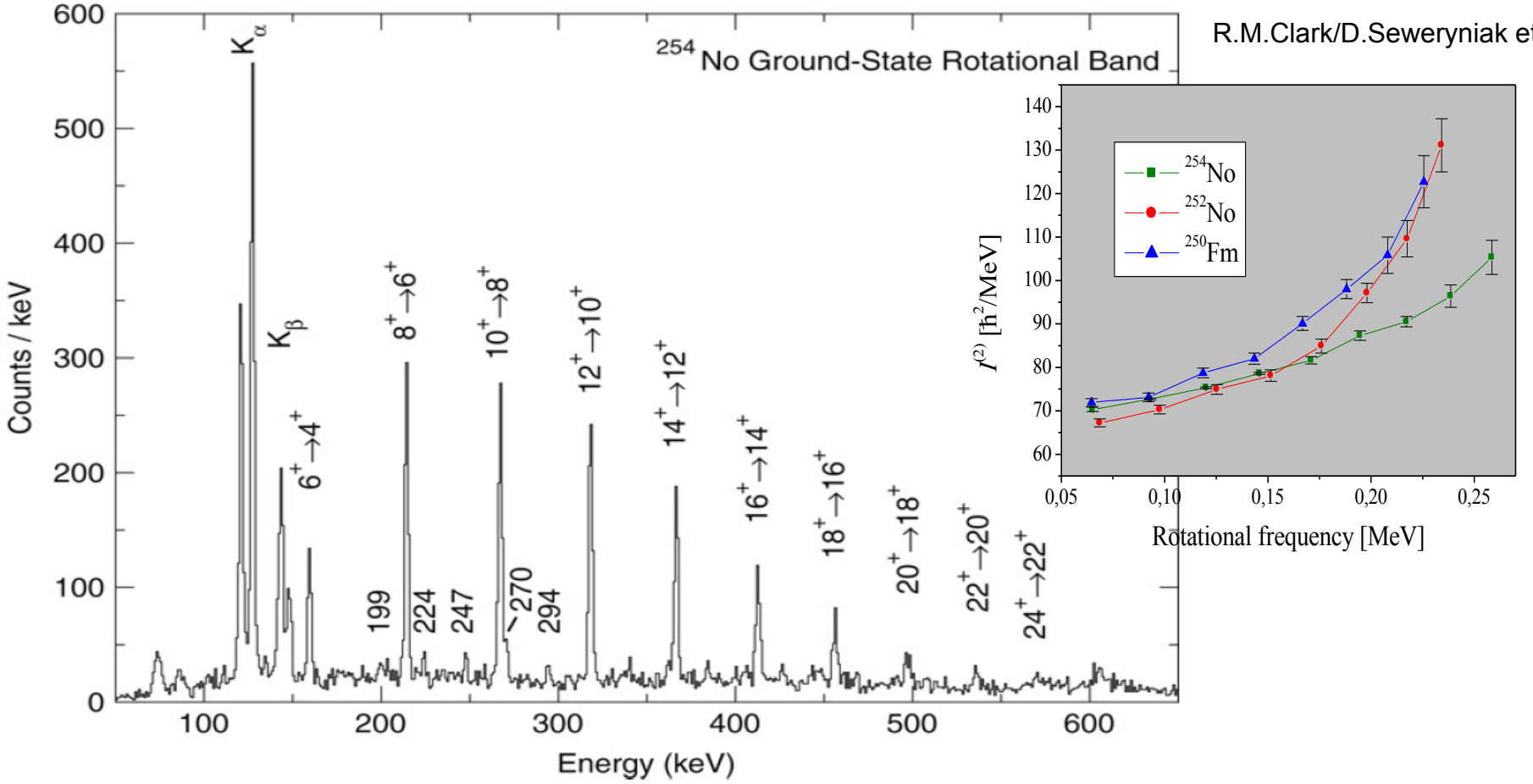
- High Intensity ^{50}Ti beam from 88-Inch, high efficiency of BGS, ANL digital daq
- Compared to lighter N=150 isotones 2qp isomer decay is x10^4 faster
- No fission observed from the isomers: fission partial lifetimes are at least 2 and 25 longer for 2qp and 4qp isomers, respectively, relative to the gs

H.M.David et al., Phys. Rev. Lett. 115 132502 (2015)

Near Term (<2018): Nobelium Spectroscopy

- Approved experiment "Towards Complete Spectroscopy of ^{254}No"
- Using Digital Gammasphere and AGFA at ATLAS/ANL

R.M.Clark/D.Seweryniak et al.



- Rotational properties of ground-state and off-yrast bands sensitive to configurations, pairing, and deformation (role of high-order multipoles)

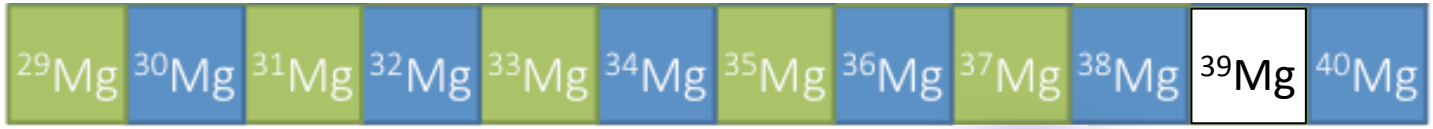
Near Term (<2018): Approved Proposals

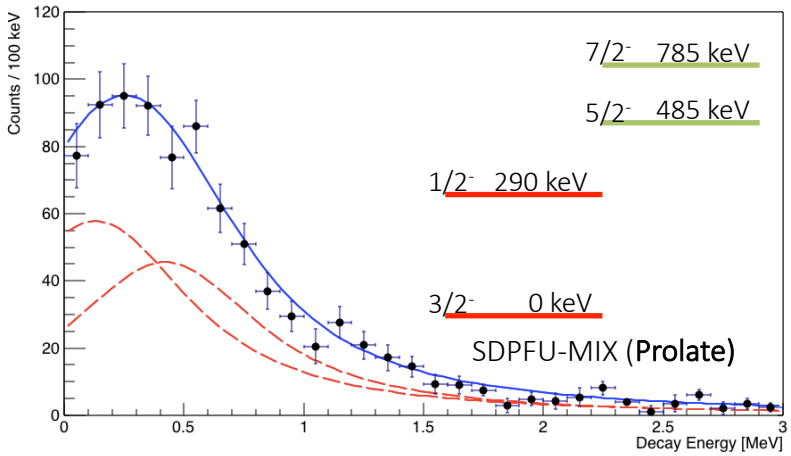
Experiment Title	LBNL Lead	Facility
One-Nucleon Transfer Reactions to Shed Light on the Calcium Puzzle	Crawford/ Macchiavelli	GRETINA @NSCL
Core Excitations in the Ground State of Neutron-Rich Fluorine Isotopes	Macchiavelli/ Crawford	GRETINA @NSCL
Identification of the First-Excited 2p2h Configuration in ^{35}P	Macchiavelli	HELIOS @ANL
Spectroscopy of ^{40}Mg	Fallon/ Crawford	RIBF/ RIKEN
Invariant Mass Measurement of ^{39}Mg at SAMURAI	Crawford/ Fallon	RIBF/ RIKEN
Search for the Giant Pairing Vibration with Neutron-Pair Transfer from ^{6}He	Clark/ Macchiavelli	TRIUMF
Pairing Vibrations Beyond N=82	Macchiavelli	TRIUMF
Toward Complete Spectroscopy of ^{254}No	Clark	ANL

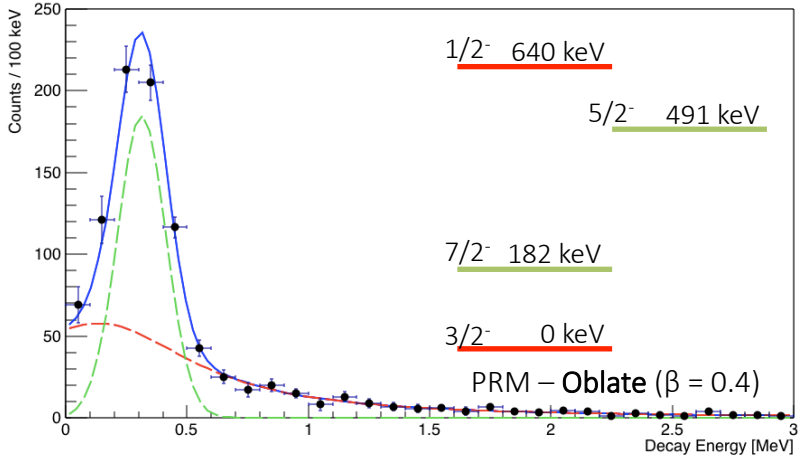
Near Term (<2018): Spectroscopy of ^{39}Mg

H.L.Crawford, P.Fallon, et al.

RIKEN







- ^{39}Mg is unbound, produced in one proton knockout from ^{40}Al on MINOS liquid hydrogen target at RIBF
- Invariant mass spectroscopy with SAMURAI+NEBULA
- Neutron decay to 0^+ in ^{38}Mg results in strong dependence on **width** depending on spin of states --> decays can only go via *l* = 1 or *l* = 3 depending on the case
- Presence of low-lying narrow component is strong evidence for oblate deformation
- Energetics may allow decay to ^{38}Mg(2^+) via different *l*, but then we will see the gamma-ray transition

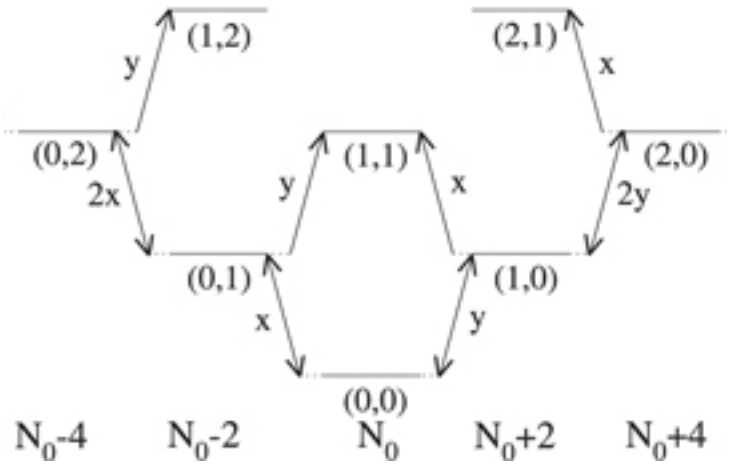
Near Term (<2018): Pairing Studies at TRIUMF

Two experiments approved at TRIUMF aimed at investigating fundamental pairing excitation modes.

TRIUMF

1) "Pairing Vibrations Beyond N=82"

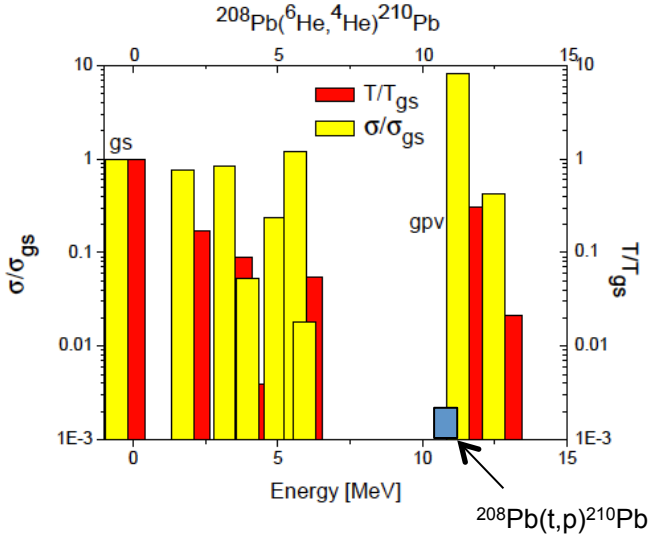
(A.O. Macchiavelli et al.)



- Theories suggesting alteration of standard picture of pairing vibrations beyond ^{132}Sn due to weak neutron-binding effects
- Testing collective pairing models by using beams of ^{134,136,138}Xe in inverse (t,p) reactions.
- SHARC (Si array) used to detect outgoing p

2) "Search for the Giant Pairing Vibration

(R.M.Clark/A.O.Macchiavelli et al.)



- Fundamental excitation mode in nuclei
- Analogous to GDR (ph channel) but now in pp channel
- Never been seen despite many attempts
- "Q-value" mismatch is suggested culprit but (^{6}He,α) reaction offers new approach.

M.Laskin, R.F.Casten, A.O.Macchiavelli, R.M.Clark, and D.Bucurescu, Phys. Rev. C 93 034321 (2016).

Long-Term Plans (>2018)

- Heavy element studies with BGS+FIONA.

  New capabilities for

  - isomer spectroscopy
  - alpha and electron capture decay spectroscopy,
  - laser spectroscopy (I, Q, μ)

- Study of exotic nuclei at RIB facilities (NSCL/RIKEN/TRIUMF)

- Strong program with GRETINA at US facilities (ATLAS/NSCL)

- Developing GRETA with a view to leading science at FRIB.

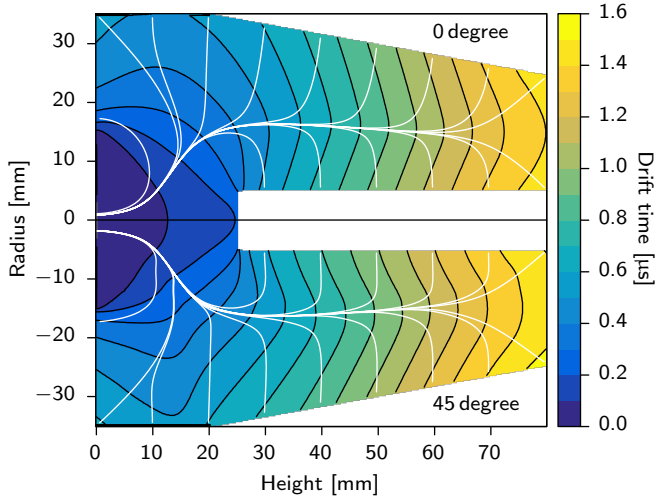
LDRD

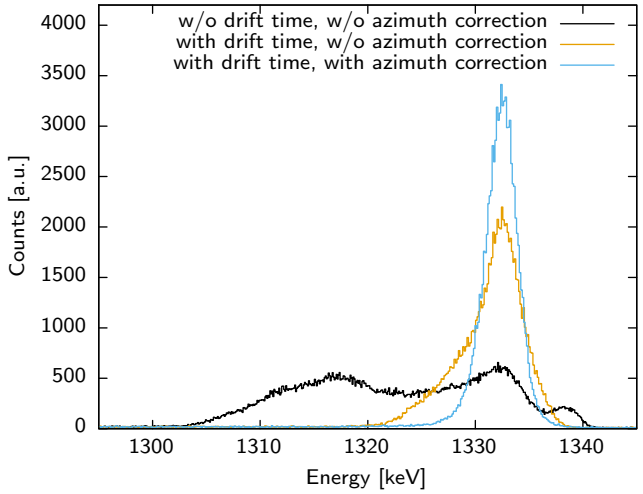
LDRD has seeded advances for our work and benefited low-energy NP community and encourages collaboration within NSD and LBNL.

Early 2000's GRETINA digitizer boards initially developed through LDRD funds.
Now widely used: - GRETINA/GRETA, Majorana Demonstrator, Digital Gammasphere

2013-2015 "Towards Laser Spectroscopy of Transfermium Elements" was initial focus enabling development of FIONA (talk by Jackie)

2016-2017 "Development of Inverted Coaxial Segmented Point-Contact HPGe Detector Technology" Heather Crawford and Ren Cooper. Post-Doc Marco Salathe (see poster).






Thanks!